A System-Wide Approach for the Integration of High Shares of Renewable Energy Sources with Particular Regard to Frequency Stabilisation

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In most countries, the energy production and transportation systems are currently in transition. With increasing shares of renewables in energy systems, mechanisms to provide grid stability are gaining importance, making the design of cheap and reliable systems complex. The paper at hand addresses these problems by establishing a system-wide approach for the integration of high shares of renewable energy sources (RES) in all energy-related sectors (i.e., heat, electricity, mobility, and industry), with a particular focus on frequency stabilisation.

The approach is based on the calculation of energy scenarios which illustrate possible transition paths to build a self-sufficient and 100 % renewable energy system by the year 2050. The results provide insights into energy demand evolution, reduction of greenhouse gas emissions, the composition of energy production, as well as storage and electricity supply costs. The balance between energy demand and supply for the targeted 100 % RES system is ensured via an analysis of different combinations of energy storage technologies. For the hybrid systems during the transition phase, an analysis of spinning conventional power plant's operational flexibility for frequency control provision is conducted. The state-of-the-art opportunity costs calculation for ex-ante capacity reservation decision is improved by including dynamic flexibility parameters and applied to historical market data. The results show that accounting for dynamic effects, such as part load efficiency or ramping costs has a notable effect on opportunity costs calculations. Further, the power plant's flexibility parameters have a significant importance to the ex-ante incentive to reserve capacity for frequency control.

The sketched methodology and results are of great relevance to India, as a regulatory framework for ancillary services is currently being conceptualised. Moreover, the comparison between Indian technical standards for thermal-based power plants and the International Energy Agency's characterisation of flexible plants shows that most Indian conventional power plants do not fulfil flexibility requirements. This demands technological and economic analyses, similar to the one presented in this paper. The methodology of the energy scenarios is applicable to the Indian energy system, especially when considering its transition toward an integrated grid.

100 % Renewable Energy Sources; Energy Scenarios; Frequencycontrol; Flexibility of Conventional Power Plants; Design of Hybrid Power Systems; Ancillary Services

I. INTRODUCTION

With increasing shares of renewable energy sources (RES) in energy systems, mechanisms to provide grid stability are becoming more important. Technical solutions are manifold and the organisation of procurement and dispatch complex. The energy production and transportation system is in transition in most countries, making the design of a cheap and reliable system challenging. This paper addresses these problems by (i) analysing the transition towards a 100 % renewable energy system via a backcasting method and (ii) discussing possible technical and organisational solutions with regard to frequency stabilisation. The following chapter sketches the methods and results of two consecutive scientific reports, in which the integration of high shares of RES in all sectors (i.e., heat, electricity, mobility, and industry) is examined for the German federal state of Lower Saxony. The reports define possible transition paths of the energy system from 2012 to a 100 % renewable goal in 2050. In the targeted system, storage technologies for balancing energy demand and supply throughout the entire year are studied. In addition to these reports, an analysis of spinning conventional power plant's operational flexibility for frequency control provision in the hybrid systems transitioning toward the 100 % RES system is conducted. The ex-ante capacity reservation decision (or ex-post capacity reservation evaluation) is improved by an approach which includes dynamic flexibility parameters and is applied to historical market data. The chosen approach allows a system-wide consideration of renewable energy integration. The transferability of the used approach to India is discussed in Chapter IV.

II. ENERGY SCENARIOS

The integration of high shares of RES in all sectors was analysed extensively for the German federal state of Lower Saxony in two consecutive scientific reports performed by the EFZN, the CUTEC Institute, and other partners (cf. [1-2]). Lower Saxony is located in northern Germany (cf. Fig. 1), has a total soil surface of 4.76 Mha and a population of 7.78 million (in 2012). In what follows, the methodology and most important results of these studies are presented. The main goal was to identify the yearly transition steps necessary to build a self-sufficient, independent and 100 % renewable energy system by the year 2050.

A. Scenarios for the energy supply in Lower Saxony in 2050

The scientific report titled „Scenarios for the energy supply in Lower Saxony in 2050“ [1] was prepared on behalf of the Ministry of Environment, Energy and Climate Protection of the German federal state of Lower Saxony. Within this work, two scenarios were developed, which were continuously discussed and improved with a large number of stakeholders (e.g., scientists, from industry and public administration). The first scenario describes an energy system based on 100 % RES. One of the objectives was the provision of this energy in accordance with energy demand profiles, with a mind to environmental sustainability, cost-effectiveness, and security of supply. On the basis of this scenario, a second scenario considering an 80 % reduction in energy-related greenhouse gas (GHG) emissions by 2050 compared to the levels in 1990 was conceptualised.

1) Essential methods

For the year 2050, a technically feasible target condition with regard to energy consumption and supply is set in each scenario. For the period from 2012 (chosen status year) to 2050, intermediate targets are defined in order to detect deviations from the projected path. This method of **backcasting** differs from the frequently used forecast method and, from the authors' point of view, avoids counter-productive developments and delays.

In the introduced scenarios, the future energy demand is covered by RES. Apart from the electricity sector, the use of RES in the supply of heat, fuels and base materials is considered for the sectors households, trade/commerce/services, industry, and transport. The assumptions concerning energy generation are made with regard to the actual potentials within the territory of Lower Saxony. They are based on the space requirements of the corresponding technologies, taking into account possible competition in usage. This ensures that the technical feasibility of the energy quantities calculated for 2050 is given and that they are compatible with each other. The **space-based approach** is implemented consistently for all technologies.

The energy consumption to be covered is calculated from the per capita energy consumption of Germany multiplied by the predicted population of Lower Saxony. The population is determined by the area of Lower Saxony and the average population density of Germany in 2012, as well as the predicted density in 2050. This so-called **solidarity approach** takes into account that a federal state with a comparatively large surface area, such as Lower Saxony, will most likely export energy generated by RES to areas outside of Lower Saxony and, in turn, import manufactured goods (solidarity region of Lower Saxony). In 2050, the predicted population of Lower Saxony will amount to 6.84 million, while the population according to the solidarity approach is 9.45 million (7.78 million and 10.73 million in 2012).

2) Most important results

Hereafter, only the most important results of the 100 % RES scenario will be illustrated. Taking into account economic development, population development, usable efficiency potentials, and a shift in fuel-based transport to electric mobility, to name a few key inputs, the resulting energy demand for the target year 2050 is reduced by 47 % compared to the status year 2012. As seen from Fig. 2, the final energy consumption is reduced from 341 TWh/a in 2012 to 182 TWh/a in 2050. At the same time, the total GHG emissions can be reduced from 125 Mt CO_2-eq/a to 17 Mt CO_2-eq/a. These remaining emissions are not energy-related and result from, e.g., industrial processes or solvents, whereas energy-related emissions are reduced to zero. Fig. 2 further shows the composition of the energy generation for different years.

With 36 %, solar energy provides the largest portion of the self-supply of Lower Saxony in 2050 assuming an installed capacity of 92 GW (plus 36 GW for export according to the solidarity approach). The second largest contribution is made by wind energy covering 30 % of the final energy consumption. A power of 20 GW of onshore wind energy in 2050 is assumed for the self-supply of Lower Saxony (plus 7 GW for the export). According to the solidarity approach, about 13 % of the energy generated in Germany from offshore wind farms is used for the solidarity region of Lower Saxony. For all of Germany, an installed capacity of 54 GW offshore wind farms is taken into account (5 GW for the

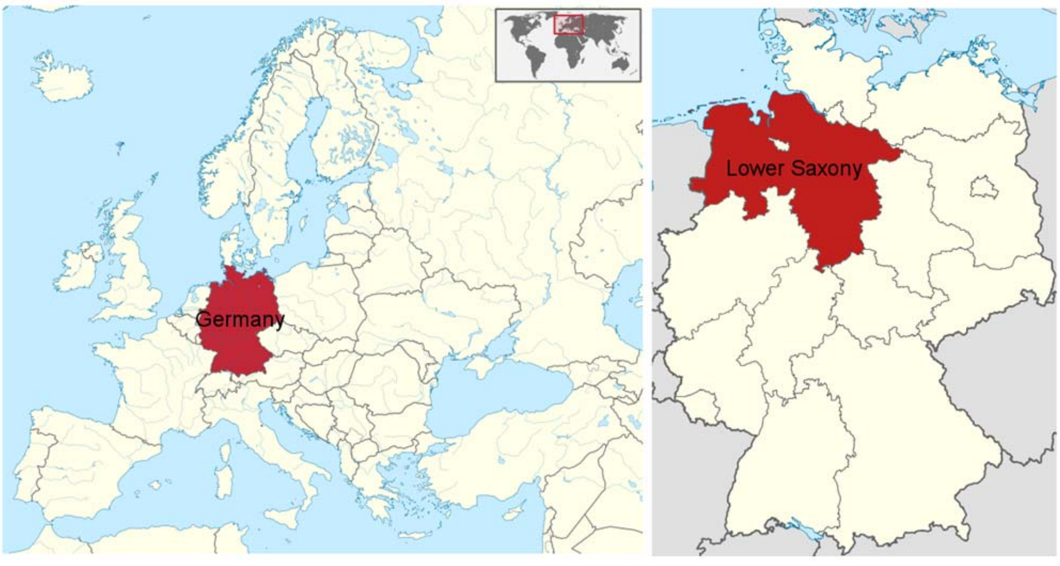

Fig. 1: Location of Germany in Europe and location of the federal state of Lower Saxony in Germany [3], [4].

self-supply of Lower Saxony plus 2 GW for solidarity export to other federal states). The third largest contributor, with around 19 % of the final energy consumption, is biomass. As a storable energy carrier with a high energy density, biomass is of great importance for the substitution of fossil fuels and as a carbon source for the production of synthetic fuels. Further portions to cover the energy consumption are ambient heat gathered by heat pumps, as well as deep geothermal energy and hydropower. In addition, the necessary storage of solar and wind energy is calculated for the year 2050 on the basis of historical generation data (i.e., of one year) and a dynamic simulation. Hydrogen was chosen as the storage medium and the calculated required storage capacity is 18.8 TWh_{H2}. This long-term storage is essential to cover the energy requirements in time periods with a low or highly intermittent energy supply. The hydrogen can also be used as a source for the production of base materials (e.g., synthetic fuels). To generate the required energy in the Lower Saxony area, 1.5 % of the soil surface (plus 0.6 % for export) is required for onshore wind parks. 3.2 % of the agricultural land (plus 1.3 % for export) and 5 % of the settlement area (plus 2 % for export) are used for photovoltaic (PV)-systems (the settlement area amounts to 8.6 % of the soil surface). For energy crop cultivation (biogas, biofuels, solid biomass), 7.9 % of the agricultural area (54.2 % of the soil surface) is used for self-supply and another 3.0 % for export according to the solidarity approach.

The calculation of energy-related and not energy-related (e.g., from industrial processes, solvents, and agriculture) GHG emissions for the year 1990 and the target year 2050 is used as a starting point for the development of the second scenario. The aim is to achieve an 80 % reduction in energy-related GHG emissions compared to the amount in 1990. This permissible contingent of emissions is calculated to 16.14 Mt CO_2-eq/a. The enabled use of fossil fuels is primarily applied to manufacture base materials, to use fuels in the mobility sector, and to generate process heat.

With regard to economic issues arising during the transition of the energy system, an assessment of the electricity supply costs (ESC) for the target scenarios is made. These ESC include electricity production costs (levelised costs of electricity), as well as additional grid and storage costs. For the scenario based entirely on RES, ESC of 11.6 cents per kWh_{el} for the final energy consumed in 2050 are determined. For the scenario with an 80 % GHG emission reduction, these ESCs amount to 11.7 cents per kWh_{el}. These results can be compared to a „Business as Usual“-case, in which the current energy system is projected onto 2050 with a large part of the system still based on fossil fuels. The ESCs in this scenario amount to 11.3-18.1 cent/kWh_{el}, depending on the price of CO_2 certificates.

In addition to the above, the variation of some influential input parameters is examined by means of various sensitivity analyses (e.g., share of electric mobility, share of mobility based on hydrogen, renovation rate of buildings, and others). As a final conclusion, potential future climate protection targets for the federal state of Lower Saxony are derived from the developed scenarios.

B. Complementary scenarios

The previously discussed scientific report [1] comprises the development of two different scenarios (100 % RES and -80 % GHG emissions). For these scenarios, the daily difference between electricity demand and supply in 2050 is calculated by dynamic simulations and historical generation data of one year. In other words, the discretisation of this simulation is one day. This is a simplification within the scope of the mentioned report. To achieve more accurate results, simulations with a higher discretisation are necessary, taking into account historical generation data from different years. In addition, the provision of ancillary services needs to be considered to evaluate the grid stability of the future energy system.

1) Simulations with a higher temporal resolution

The aim of a complementary scientific report [2], which was also prepared on behalf of the Ministry of Environment, Energy and Climate Protection, was the development of scenarios based on simulations with a higher temporal resolution (i.e., discretisation of 15 min). These scenarios are a supplement to the scenarios developed in the thus far illustrated report [1]. The task of these complementary considerations is, inter alia, to examine measures for influencing long-term storage requirements. In this context, a more detailed analysis of the influence of short-term storages is carried out.

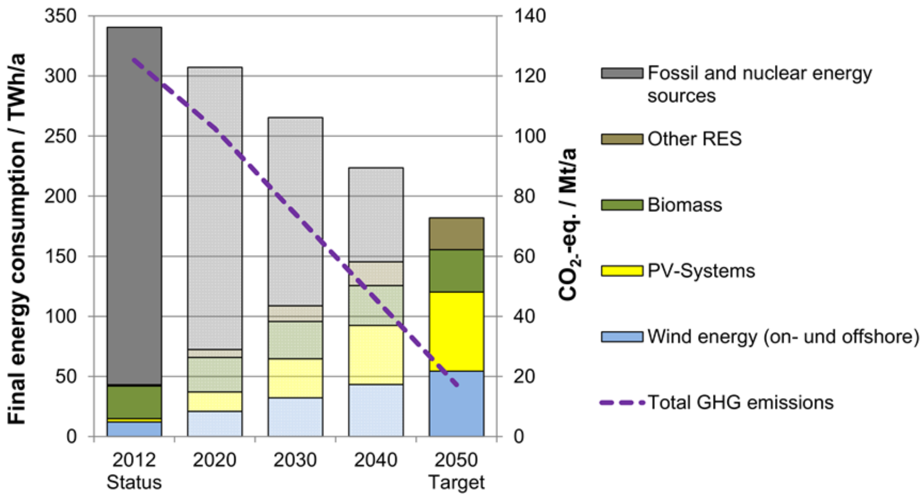

Fig. 2: Development of the final energy consumption divided by energy sources and the total amount of GHG emissions for the federal state of Lower Saxony and the 100 % RES scenario [1].

The simulations within this second report are performed via a MATLAB®-based simulation programme called "Renewable Lower Saxony" (ReLoS), which was designed at the Institute for Solar Energy Research Hamelin, ISFH in Germany [2].

Based on an initial reproduction of the 100 % RES scenario of the first report, further storage-specific scenarios are selected and analysed. Within the scope of this work, only a small part of the results can be presented. The scenarios are examined based on a cost optimisation conducted using the ReLoS program. Long-term energy storages using water electrolysis and hydrogen are considered within all scenarios, while they differ regarding other parameters:

- Scenario with only lithium-ion batteries as short-term storages
- Scenario with only pumped-storage power plants as short-term storages
- Scenario with an increased capacity of buffer thermal storages
- Scenario with an increased solar thermal power for hot water preparation

The cost-driven optimisation shows that the case based solely on a long-term storage is the most cost-effective of all scenarios considered. Short-term storages are less favourable with regard to their costs. Therefore, an expansion path is calculated for this scenario only (cf. Fig. 3). The figure shows that water electrolysis is not required until the year 2020. According to the results, a linear increase in the electrolysis power to the target value of this scenario of 34.8 GW will be required. The demand for storage (cavern) capacity remains small until the year 2040 (<1.1 TWh), but rises to 35.6 TWh by 2050.

The costs of different energy systems calculated in the scenarios vary by up to 30 %. The uncertainty about the assumed component prices in 2050 is quite large. Consequently, the presented results should indicate which configurations are possible. However, they should not be misunderstood as a recommendation to abandon certain technologies. The data basis is too uncertain from today's point of view. The fact that different system configurations lead to similar costs gives the stakeholders and politicians a great scope for action. They can use this to promote acceptance and support the implementation of the energy transition („Energiewende“).

2) *Analysis of grid stability*

In order to evaluate the grid stability of the fully renewable energy system, technical solutions for the provision of ancillary services are considered in [2]. The analysis of the 100 % RES scenario shows that with the intended components a secure power supply can be guaranteed for 4,757 h of the year 2050 (i.e., mainly by operating hydrogen fueled power plants). For the remaining hours, new procedures are presented taking into account current research results and exemplary technical solutions. On this basis, options for a 100 % renewable energy system in Lower Saxony are proposed using an exemplary calculation. It is shown that in such an energy system the balancing of energy demand and supply is possible, but in the case of a system with more heterogeneous components further research is required. The remainder of this paper thus focusses on the frequency control in the transitional (hybrid) system and explores spinning conventional power plant’s flexible operation.

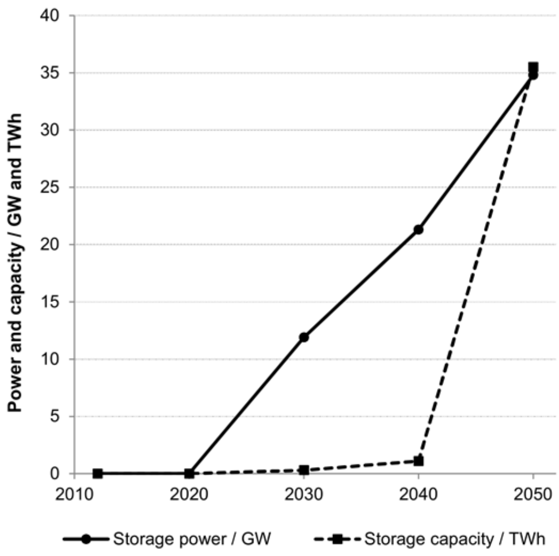

Fig. 3: Expansion path of long-term energy storage (water electrolysis) in Lower Saxony [2].

III. Frequency stabilisation

A. Frequency control: Lessons learned from Europe

With regard to technical and organisational solutions for grid safety and cost efficiency under high renewable energy supply, the European system offers interesting insights. In the German system, empirical market data has shown that despite increases in the share of volatile RES in the energy system, a reduction in frequency control capacity and costs can be realised [5]. The interested reader can refer to [6] and [5] for the rules and functioning of these markets. The roadmap proposed in [6] can be complemented by the lessons learned in Europe, especially in terms of control procurement by intermittent resources. The latter is facilitated by more frequent tendering and shorter time periods [5]. Shorter lead times present a further advantage. Reference [5] suggests conditional bidding, which could help reduce the system must-run capacities. For cost efficiency [5] proposes marginal pricing instead of pay-as-bid auctioning. In order to reduce the frequency control costs, a good intraday market is required, as the tripped capacity can be replaced by the capacity contracted on this market. A sufficient intraday liquidity reduces the need for forecast error-related frequency control [5]. Please refer to Table 8 of [5] for further policy recommendations. The determination of the required reserve capacity varies strongly between European countries, refer to [5] for discussion.

The scope of this paper is limited to control power and thus neglects imbalance settlement aspects. It includes operating as well as contingency reserves, spinning reserves, positive as well as negative reserves, all activation times and ways of activation (cf. [5], chapter 2.4 for terminology). The various frequency control markets in Europe show similarities in design but some differences in implementation. The review and lessons learned in Europe in terms of public procurement auction design (pricing, lead times, bidding periods etc.) are used to model a single organisational framework, which can be parametrized to model different markets. The model parameters and possible parameter values are detailed in Table 1. This very simple parametric model includes all relevant aspects of frequency control capacity reservation apart from lead times, as perfect price foresight is assumed in the following.

Tab. 1: Frequency control parametric model

	Description	Possible values	Exemplary value
Program unit size	Duration for which the service needs to be made available	Year, month, week, day, block of hours etc.	Week
Minimum bid size	Minimum capacity to be bid in the market	Typically between 1 and 5 MW	5MW
Full activation time	Duration within which the full committed capacity needs to be provided	Typically between 30s and 15 minutes	5 minutes
Peak and off-peak product	Peak and off-peak products correspond to a high and low tariff period differentiation	Any high vs low tariff differentiation	The peak product is between 8:00 and 20:00 for weekdays. The rest is off-peak.
Symmetrical product	The service can be either symmetric, (positive and negative control is required) or not symmetric (positive or/and negative).	Symmetric or non-symmetric	Non-symmetric

B. Ex-ante capacity reservation decision

As conventional power plants are able to support the energy transition by ensuring frequency control, this section explores some key aspects of spinning conventional power plant´s flexible operation in such a system. Regarding the technical flexibility requirements and technical solutions for compliance, the interested reader can refer to [5-6] for the market and frequency control provision rules and [7-10] for technical solutions for increasing power plant flexibility. The paper at hand specifically observes how capacity reservation affects the power plant´s dispatching problem and economics in an organisational framework of the type characterised above (cf. Table 1). The problematic addressed here does not lie in the energy dispatch and payment but the capacity reservation (two-part tariff) and the related opportunity costs. The plant operator has to decide ex-ante whether to participate or not and to do so needs to calculate opportunity costs. These represent the value of the loss of gain that is incurred when selecting the option to reserve capacity in the frequency control market preferably to the option to do not. Please refer to [5] for the theory of opportunity costs in a liberalised competitive electricity market. The state-of-the-art opportunity cost calculation is here extended with the following two features: (i) opportunity costs accounting for dynamic effects such as part load efficiency or ramping costs and (ii) opportunity cost calculation for program unit sizes (here a week) differing from the electricity market program unit size (typically an hour).

For the opportunity costs calculation, two cases are to be differentiated: either the power plant´s marginal operation costs are above the electricity price (out-of-merit case) or they are below (in-merit case). The opportunity costs equal the foregone profits for infra-marginal plants and the incurred losses for the others. When using opportunity costs calculations for ex-ante decisions in a deterministic approach, perfect price foresight has to be assumed. Stochasticity can easily be accounted for via the use of various price scenarios.

1) Out-of-merit case opportunity cost calculation

Without any given must-run condition, a power plant operator would not operate the plant unless its marginal operation costs c_p are below the electricity price EP. In case of positive capacity procurement Δ_{pos} in the frequency control market, the plant has to operate at minimum technical load x_{min} at least. For negative procurement, the load level should be at least $x_{min} + \Delta_{neg}$. In the literature, these opportunity costs do not take into account the increased operation costs at part load, and constant marginal costs are assumed. With this assumption, the opportunity costs c_i (t)of an out-of-merit power plant are the losses allocated to the offered control capacity as in (1) and (2). If the dynamic effect of the efficiency loss at part load needs to be taken into account, the losses can be written as in (3) for a given load level p, with p either x_{min} or $x_{min} + \Delta_{neg}$, $f(p(t))$ the corresponding fuel consumption with fuel prices $FP(t)$ and c_m $(p(t))$ the corresponding maintenance costs.

$$c_i(t)=(c_p(t)-EP(t))\cdot\frac{x_{min}}{\Delta_{pos}} \quad \forall t \mid EP(t)<c_p(t) \qquad (1)$$

$$c_i(t)=(c_p(t)-EP(t))\cdot\frac{x_{min}+\Delta_{neg}}{\Delta_{neg}} \quad \forall t \mid EP(t)<c_p(t) \qquad (2)$$

$$c_i(t)=\frac{FP(t)\cdot f(p(t))+c_m(p(t))-EP(t)\cdot p(t)}{\Delta} \quad \forall t \mid EP(t)<c_p(t) \qquad (3)$$

2) In-merit case opportunity cost calculation

In case the power plant´s marginal operation costs are below the day-ahead electricity price, the opportunity costs are the foregone profit allocated to the control capacity. The positive control capacity reserved in the control market is no longer available for the day-ahead market. The opportunity costs equal to zero when the day-ahead electricity price equals the marginal costs of the plant. In the case of negative control power, the infra-marginal power plant opportunity costs equal zero, as no profitable capacity is reserved, as in (4) and (5). If the dynamic effect of the efficiency loss at part load needs to be taken into account, the foregone profits for positive capacity can be written as in (6).

$$c_i(t)=\frac{\left(EP(t)-c_p(t)\right)\cdot\Delta_{pos}}{\Delta_{pos}} \quad \forall t \mid EP(t)\geq c_p(t) \qquad (4)$$

$$c_i(t)=0 \quad \forall t \mid EP(t)\geq c_p(t) \qquad (5)$$

$$c_i(t)=\frac{EP(t)\cdot\Delta_{pos}-FP(t)\cdot f\big(p(t)+\Delta_{pos}\big)}{\Delta_{pos}}+\frac{-c_m\big(p(t)+\Delta_{pos}\big)+FP(t)\cdot f\big(p(t)\big)+c_m\big(p(t)\big)}{\Delta_{pos}} \quad \forall t \mid EP(t)\geq c_p(t) \tag{6}$$

3) Decision criteria for entire program unit size

The decision to participate or not in the market during the period PUS (program unit size) during d_i hours is based on the comparison of the opportunity costs (calculated via the day-ahead electricity price and operation costs) and the capacity prices on the frequency market (perfect foresight is assumed). The participation decision criteria is thus submitted to the comparison of the integrated opportunity costs C_i and the profits on the control market, which is the capacity price CP, as in (7). If the condition is true, capacity should be reserved.

$$C_i(d_i)=\frac{1}{PUS}\int_0^{d_i} c_i(t)\mathrm{d}t< CP \tag{7}$$

C. Data set and calculation

The capacity reservation opportunity costs as derived in the previous section are dependent on various parameters and time series:

- The price at which electricity is rewarded, here for the calculations the German day-ahead spot prices
- The power plant marginal operation costs, which are assumed constant over time
- The reserved capacity, with the positive and negative servable control being assumed equal. The reserved capacity is assumed to be the maximum servable capacity, thus the product of the power plant ramp rate and the control activation time.
- The power plant minimum technical load

The calculations are performed using the data of the second week of the year 2014, from the 6th to the 12th of January. The capacity reservation price signal used in the following is the weighted average of the secondary frequency control market results in Germany, as the market is organised as a pay-as-bid market. There are four products to be accounted for, as the market is non-symmetric (negative and positive control) and as there are two tariff periods (high and low tariff). This matches the exemplary values of the parametric model to be found in Tab. 1.

D. On the importance of efficiency losses at part load and any other dynamic effect

Fig 4 illustrates exemplary opportunity costs in the secondary and minute market for a given power plant depending on the electricity prices. The opportunity costs are first calculated without taking efficiency losses at part load and any other dynamic effects like cycling costs into account. For the selected power plant, marginal operation costs of 25€/MWh and ramp rates of 3% per minute are assumed. Due to the higher activation time in the minute market, more capacity can be offered (plant parameters remaining equal). The opportunity costs are lower. For a given market, the opportunity costs are higher in the out-of-merit case (the electricity prices are lower than the marginal operation costs) than in the in-merit case. This is due to the obligation to operate at minimum technical load (spinning control) despite low rewards on the electricity market.

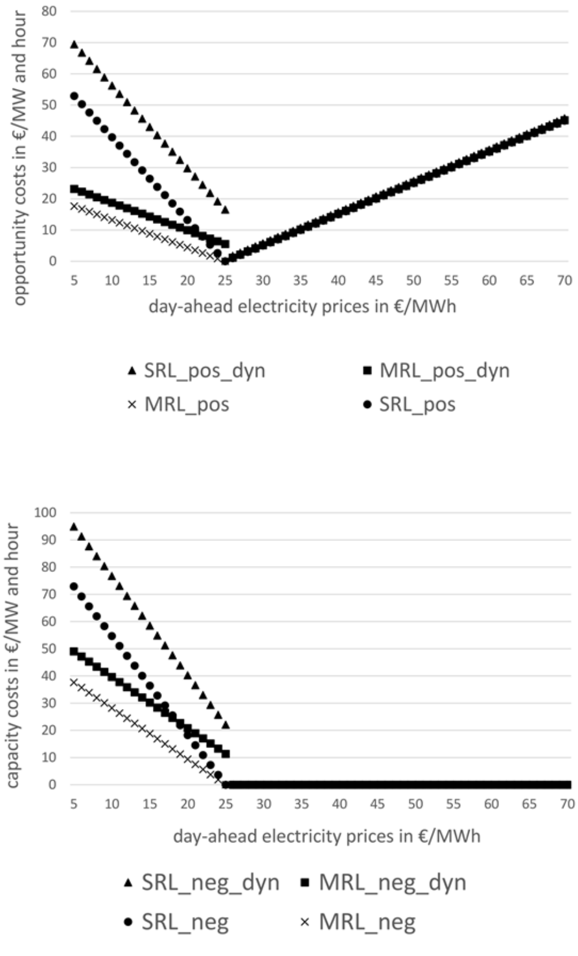

Fig. 4: Comparison of opportunity costs for positive (above) and negative (below) frequency control capacity provision when accounting for dynamic effects or not. SRL: secondary control. MRL:tertiary control. POS: positive control . NEG:negative control. Dyn: with dynamic effects

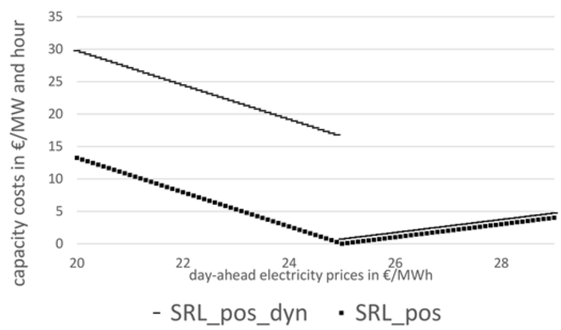

Fig. 5: Opportunity costs for positive frequency control capacity provision when accounting for dynamic effects. SRL: secondary control. Dyn: with dynamic effects. POS: positive control

For the quantitative assessment of dynamic effects such as the reduced power plant efficiency at part load, a second opportunity costs calculation is made assuming an 8.8 percentage point efficiency loss at minimum technical load. The opportunity costs in dependence of the electricity price for a given power plant differ when accounting for dynamic effects, as can be seen in Fig 4. The results show that these aspects should not be left out of the calculations. When the electricity price reaches the power plant´s marginal operation cost, the opportunity costs for positive control no longer equal zero, but the difference in operation costs due to the efficiency loss at minimum load. As soon as the electricity prices surpass the plant´s marginal operation costs, the opportunity costs become the difference in operation costs due to the efficiency loss at the operated load (here the nominal load minus the reserved positive capacity), see Fig 5.

E. Merit order of opportunity costs

The following calculations include program unit sizes (here a week) differing from the electricity market program unit size (here an hour). Fig. 6 illustrates the merit order of capacity reservation opportunity costs for the first week of the year 2014. For that week, the capacity reservation was only beneficial during high tariff times, and for power plants with marginal operation costs lower than about 34€/MWh. Interestingly, in the case of positive capacity reservation during the high tariff period, power plants with marginal operation costs lower than about 24€/MWh should not offer capacity. During the high tariff periods of that week, the spot prices are higher than 30€/MWh, so that these power plants are always in-merit. With shrinking marginal operation costs, the profits in the day-ahead market increase accordingly and the incentive to offer capacity reduces concomitantly.

The same calculations are performed using modified flexibility parameters in order to assess the influence of ramp-rates and/or minimum load quantitatively. Improved operational flexibility primarily increases the capacity that can be offered on the market. With the increase of servable capacity, the opportunity costs decrease, and capacity reservation is profitable for plants with higher marginal operation costs. For instance, increasing the servable capacity from 10MW to 30MW allows for an increase in tolerable marginal operation costs to 36€/MWh, see Fig. 7.

F. Conclusion

The various assessments presented here lead to the conclusion that (i) accounting for dynamic effects such as part load efficiency or ramping costs has a notable effect on opportunity costs calculations and (ii) the power plant´s flexibility parameters have a significant importance to the ex-ante incentive to reserve capacity for frequency control, primarily driven by the servable capacity. The power plant´s operational flexibility does not directly impact the frequency control energy provision, as the latter is a prerequisite to the participation to the frequency control market and as different bid strategies can be put in place to increase or decrease the probability of a call (two-part tariff markets). Analyzing the influence of the operational flexibility cost structure on the bidding strategy and energy call probability might be an interesting topic for further research.

IV. Relevance for India

According to the International Energy Agency’s (IEA) characterization, flexible coal plants should offer ramping rates of 4-8 % of nominal load per minute and minimum outputs of 20 to 40 % [11]. India’s Central Electricity Authority (CEA) sets the technical standards for the construc-

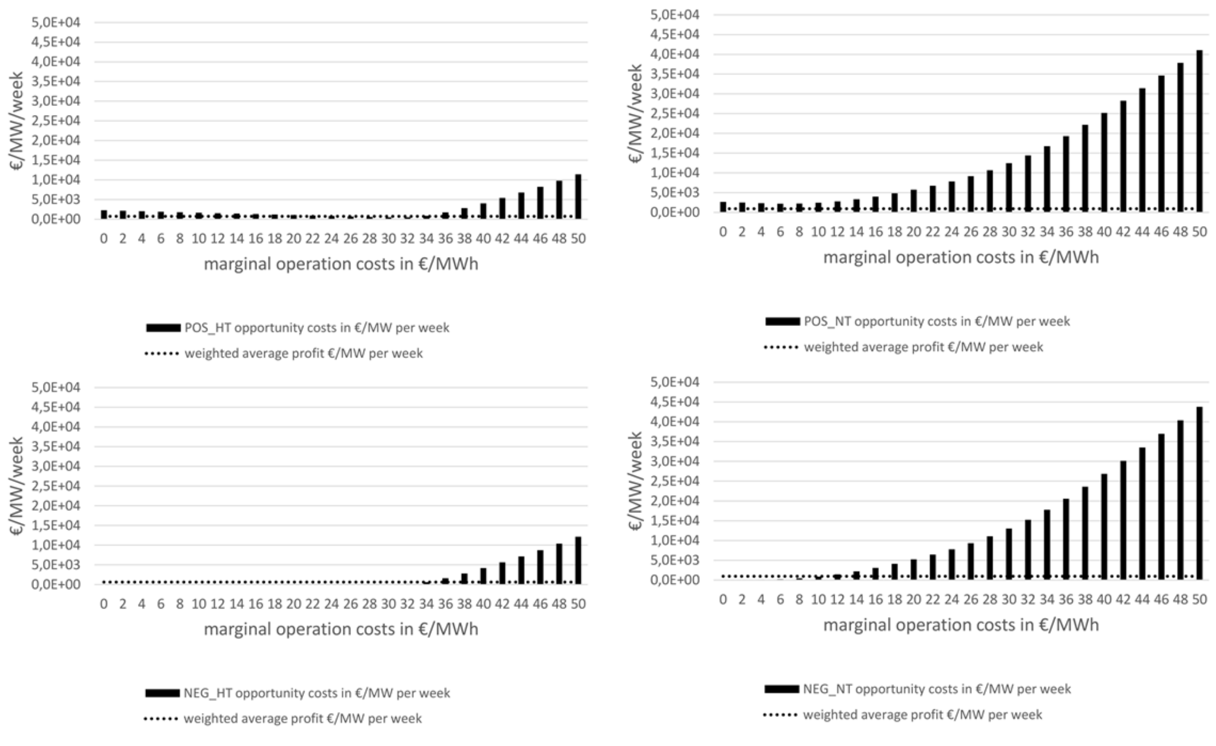

Fig. 6: Merit order of frequency control capacity provision opportunity costs- Calculation without dynamic effects. POS: positive control. NEG:negative control. HT: high tariff. NT: low tariff

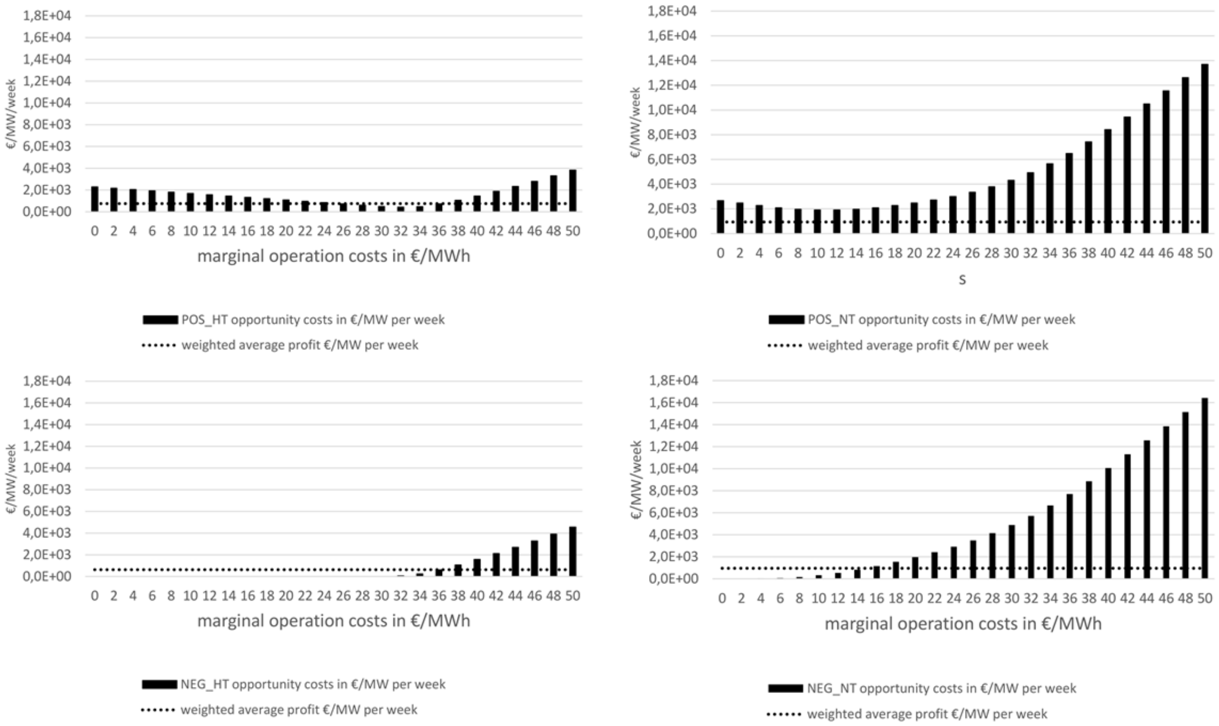

Fig. 7: Merit order of frequency control capacity provision for a more flexible power plant- Calculation without dynamic effect. POS: positive control. NEG:negative control. HT: high tariff. NT: low tariff

tion of supercritical thermal based power plants to a minimum rate of loading or unloading of 3 % per minute above the control load: 50 % according to the CEA or 55 % to the Central Electricity Regulatory Commission (CERC) [12]. When compared to the IEA's standards, this does not provide for flexible operation. It has further been assessed that actual ramp rates are usually lower than the prescribed 3 % per minute [12]. In order for Indian power plants to become more flexible, they have to be analysed for their suitability to retrofit, from a technological and economic point of view. The calculations above of spinning conventional power plant's opportunity costs offer a good basis for this assessment, as they account for operational flexibility.

Additionally, the Indian National Electricity Policy stipulates that a spinning reserve of at least 5 % at national level is needed to secure grid stability, as well as an overall availability of installed capacity of 85 % [11]. Until 2003, the ancillary services needed to stabilise the grid were provided by vertically integrated utilities. With the liberalisation of the electricity market, the need of an ancillary services market arose. [13]. In 2015, CERC drafted a regulatory framework with the objective to balance the frequency level of the grid via increased/decreased generation, called the Ancillary Services Operation Regulations [14]. The establishment of a frequency control market and the growing liberalisation of the electricity market allows for the transferability of the opportunity costs calculations to the Indian market [15]. According to a roadmap proposed by the Indo-German Energy Programme, an operational market for automatic generation control could be realised by the year 2022 [6]. Furthermore, India aims at achieving a 40 % share of RES in its energy mix until 2030 [16].

With this, India's climate protection targets are in line with the established climate protection agreements that exist in Germany (Climate Protection Plan of the German Federal Government) [17] as well as on a European (Energy Union) [18], and on a global level (Paris climate agreement) [19]. This calls for a deepening and broadening of mutual relations by means of increased cooperation, as well as knowledge and technology transfer.

The energy scenarios drafted for the state of Lower Saxony (cf. [1-2]) can be transferred to several Indian states in order to sketch possible pathways toward this targeted RES share and beyond 2030. For instance, Lower Saxony has a RES share of 46 % in the electricity sector, produced by 12.9 GW installed renewable capacity and approx. 10 GW of installed conventional capacity [20-22]. These figures are comparable to those of Tamil Nadu (installed renewable capacity 10.7 GW, installed conventional capacity 13.1 GW) and Karnataka (installed renewable capacity 8.2 GW, installed conventional capacity 7.1 GW) [23]. The energy potential of the respective region could be assessed in the space-based approach chosen in the study. It considers the space consumptions of the technologies relevant for harvesting these potentials [1]. This approach can easily be adapted to the geographic conditions of the aforementioned Indian states.

Since the beginning of this century, the focus of planning the generation and transmission system shifted from regional self-sufficiency toward a more optimal allocation of energy resources throughout India [24]. The solidarity approach applied in [1] can be transferred to the Indian system, as the grid has transitioned to a more integrated state [24].

V. Conclusion

Two studies on the integration of high shares of RES in all sectors (e.g. heat, electricity, mobility, and industry) were prepared for a German federal state, the results of which can be transferred to several Indian states. Scenarios based on a backcasting methodology combined with a space-based approach and solidarity approach lead to possible pathways and yearly steps necessary to build a self-sufficient, independent and 100 % renewable energy system by the year 2050. These results provide insights into energy demand evolution, energy- and not energy-related GHG emission reduction, the composition of energy production as well as storage and electricity supply costs. The targeted 100 % RES system's balance of energy demand and supply has been analysed in detail. Potential generation technologies have been quantified and different energy storage scenarios examined. For the hybrid systems transitioning toward the 100 % RES goal, an analysis of spinning conventional power plant's operational flexibility for frequency control provision has been made. The state-of-the-art opportunity costs calculation for ex-ante capacity reservation decision (or ex-post capacity reservation evaluation) was improved by including dynamic flexibility parameters and applied to historical market data. This shows that accounting for dynamic effects such as part load efficiency or ramping costs has a notable effect on opportunity costs calculations. Further, the power plant's flexibility parameters have a significant importance to the ex-ante incentive to reserve capacity for frequency control, primarily driven by the servable capacity. This is of relevance to India, as a regulatory framework for frequency level balancing is currently being conceptualised. Moreover, the comparison between Indian technical standards for thermal-based power plants and IEA's characterisation of flexible plants has shown that most Indian conventional power plants do not fulfil flexibility requirements. This demands technological and economic analyses, which this paper presents. In this regard, the energy scenario methods, namely the space-based approach and the solidarity approach combined with a backcasting methodology, can be applied to the Indian system, especially when considering the transition of India's electricity system toward an integrated grid.

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